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14. ABSTRACT
The objective of this instrumentation proposal is to develop a state-of-the-art micro-air-vehicle (MAV) test facility at Texas A&M University. This will be capable of measuring not only the fixed-frame hub loads, but also the blade airloads/surface pressure distribution in the rotating frame and the unsteady flowfield. The test rigs will be designed to have the resolution and bandwidth to accurately measure low-magnitude/high-frequency airloads and also resolve highly-unsteady/vortex-dominated velocity field, which are typical of these small-scale hovering concepts such as cycloidal rotors, flapping wings, and conventional rotors. All the different equipment included in this

15. SUBJECT TERMS
MAV, PIV, flapping wing, cycloidal rotor, rotorcraft

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Report Title

Final Report: Instrumentation for Performance, Blade Loads and Flowfield Measurement of Novel Hover-Capable Meso-Scale Aerial Platforms

ABSTRACT

The objective of this instrumentation proposal is to develop a state-of-the-art micro-air-vehicle (MAV) test facility at Texas A&M University. This will be capable of measuring not only the fixed-frame hub loads, but also the blade airloads/surface pressure distribution in the rotating frame and the unsteady flowfield. The test rigs will be designed to have the resolution and bandwidth to accurately measure low-magnitude/high-frequency airloads and also resolve highly-unsteady/vortex-dominated velocity field, which are typical of these small-scale hovering concepts such as cycloidal-rotors, flapping-wings, and conventional rotors. All the different equipment included in this proposal, such as the state-of-the-art Particle Image Velocimetry (PIV) system, the force transducers, high-bandwidth mems-based micro pressure sensors and data acquisition system are already in place and are currently being used to conduct high quality time-resolved measurements of the blade loads, pressure distribution/flowfield around the blade and in the wake for both steady hover and transient conditions.
PI has undertaken many DoD sponsored MAV projects including one task from ARO and another one as part of Army/Navy/NASA-sponsored VLRCOE at Maryland all requiring such a comprehensive test facility to understand the aeromechanics of novel MAV systems and also generate high-fidelity test data for model-validation purposes.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Moble Benedict: 2016 AHS François-Xavier Bagnoud Award for career-to-date contribution to vertical flight technology under the age of 35.
Carl Runco: 2016 AHS Robert L. Lichten Award for the paper titled "Development of the World's Smallest Cyclocopter".
David Coleman: Best Paper Award in Advanced Vertical Flight Session of 2016 American Helicopter Society Annual Forum.
Brett Himmelberg: 2016 AHS Vertical Flight Foundation Scholarship (undergraduate category)
Carl Runco: First prize in the Annual AIAA Region IV Student Conference 2016 (graduate category)
Brett Himmelberg: First prize in the Annual AIAA Region IV Student Conference 2016 (undergraduate category)
Adam Kellen: Second prize in the Annual AIAA Region IV Student Conference 2016 (undergraduate category)

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Project Summary - Grant # M1503193 (DURIP)
(Reporting Period: September 2015 – November 2016)

PERFORMANCE, BLADE LOADS AND FLOWFIELD MEASUREMENT OF NOVEL HOVER-CAPABLE MESO-SCALE AERIAL PLATFORMS (DURIP)

Moble Benedict
Aerospace Engineering Department
Texas A&M University, College Station, MD, 77843

Objective

The goal of this instrumentation proposal is to develop state-of-the-art micro air vehicle (MAV) test facilities at Texas A&M University (TAMU). This will be capable of measuring not only the fixed-frame hub loads, but also the blade airloads/surface pressure distribution in the rotating frame and the unsteady flowfield. The test rigs will be designed to have the resolution and bandwidth to accurately measure low-magnitude/high-frequency airloads and also resolve highly-unsteady/vortex-dominated velocity field, which are typical of these small-scale hovering concepts such as cycloidal-rotors, flapping-wings, and conventional rotors.

Approach

Use the proposed instrumentation to develop a state of the art experimental facility, which can be adapted to conduct force, pressure distribution and flowfield measurements on a wide range of hovering MAV concepts such as cyclorotors, flapping wings and also conventional rotors. All the different equipment included in this proposal, such as the state-of-the-art Particle Image Velocimetry (PIV) system (5.5 MP CMOS camera, 70 mJ Nd:YAG laser, etc.), the force transducers, high-bandwidth mems-based micro pressure sensors and data acquisition system, will all be part of these MAV testing facilities that is being developed at PI's *Advanced Vertical Flight Laboratory* at Texas A&M. These are currently being used to conduct high quality time-resolved measurements of the blade loads, pressure distribution/flowfield around the blade and also in the wake, not only in steady hover conditions, but also in transient conditions. The understanding gained will enable the development of more efficient vehicle configurations, which are also highly robust to external perturbations.

Relevance to Army

Currently, at TAMU, PI has undertaken many DoD sponsored MAV projects including one task from ARO and another one as part of Army/Navy/NASA sponsored Vertical Lift Research Center of Excellence (VLRCOE) at Maryland all requiring such a comprehensive test facility to understand the aeromechanics of novel MAV systems and also generate high-fidelity test data for model-validation purposes. This equipment request is crucial to these projects and will be a significant step in the direction towards the development of next-generation meso-scale hover-capable aerial robotic platforms for Army and Department of Defense (DoD) applications. Developing such a comprehensive facility to explore MAV/UAV technical issues and to train future scientists and engineers in their use, will have a broad impact on relevant DoD research activities.

Accomplishments for Reporting Period

- A key equipment acquired as part of this award is a state-of-the-art Particle Image Velocimetry (PIV) system (5.5 MP CMOS camera, 70 mJ Nd:YAG laser, etc.), which is currently being used for conducting detailed flowfield measurements around a cycloidal rotor blade (see subsequent sections for details).
- The miniature ATI six component balance is acquired and is currently used for measuring the instantaneous blade loads on a cycloidal rotor (see subsequent sections for details).
- The miniature Endevco pressure sensors were used to measure the pressure distribution around a blade in a wind tunnel (see subsequent sections for details).
- The Transducer Techniques load cells along with National Instruments data acquisition systems have been used for developing multi-component balances for measuring the performance of MAV-scale cycloidal rotors, flapping-wings and conventional rotors (see subsequent sections for details).

Collaborations and Technology Transfer

- None

Resulting Publications During Reporting Period

- Runco, C., Coleman, D., and Benedict, M., "Development of the World's Smallest Cyclocopter," Submitted to the *Journal of the American Helicopter Society*.
- Runco, C., Coleman, D., and Benedict, M., "Development of the World's Smallest Cyclocopter," Proceedings of the 72nd Annual National Forum of the American Helicopter Society, West Palm Beach, FL, May 17–19, 2016.
  (2016 American Helicopter Society Robert L. Lichten Award Winner)
- Coleman, D., and Benedict, M., "System Identification of a Robotic Hummingbird in Hovering Flight," Proceedings of the 72nd Annual National Forum of the American Helicopter Society, West Palm Beach, FL, May 17–19, 2016.
  (Best Paper Award Winner in the Advanced Vertical Flight Session)
- Yang, X., Sudhir, A., and Benedict, M., "Nonlinear Aeroelastic Model for Highly Flexible Flapping Wings in Hover," Proceedings of the 72nd Annual National Forum of the American Helicopter Society, West Palm Beach, FL, May 17–19, 2016.
- Runco, C., Coleman, D., and Benedict, M., "Design and Development of a Meso-Scale Cyclocopter," Proceedings of the AIAA SciTech, San Diego, CA, Jan 4–8, 2016.

Graduate Students Involved During Reporting Period

- David Coleman (PhD, current)
- Carl Runco (PhD, current)
- Atanu Halder (PhD, current)
- Carolyn Walther (M.S., current)

Awards, Honors and Appointments

- Moble Benedict: **2016 AHS François-Xavier Bagnoud Award** for career-to-date contribution to vertical flight technology under the age of 35.
- Carl Runco: **2016 AHS Robert L. Lichten Award** for the paper titled “Development of the World’s Smallest Cyclocopter”.
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Description, Pictures of Facilities Developed and Sample Results Using DURIP Instrumentation

1. PIV Cameras and Electronics

1.1. Imager sCMOS Camera

Megapixel scientific CMOS (sCMOS) camera with global shutter and double-frame mode for cross correlation PIV, CCD-resolution:2560 x 2160 pixel at 50 Hz.

1.2. Scientific camera lens and filter

Camera lens is Nikon 50 mm focal length, F/1.4, F-mount. The camera filter is Narrow band pass, 532 nm +/- 10 nm, 95% transmission efficiency at 0 degree incidence angle, 52 mm diameter.

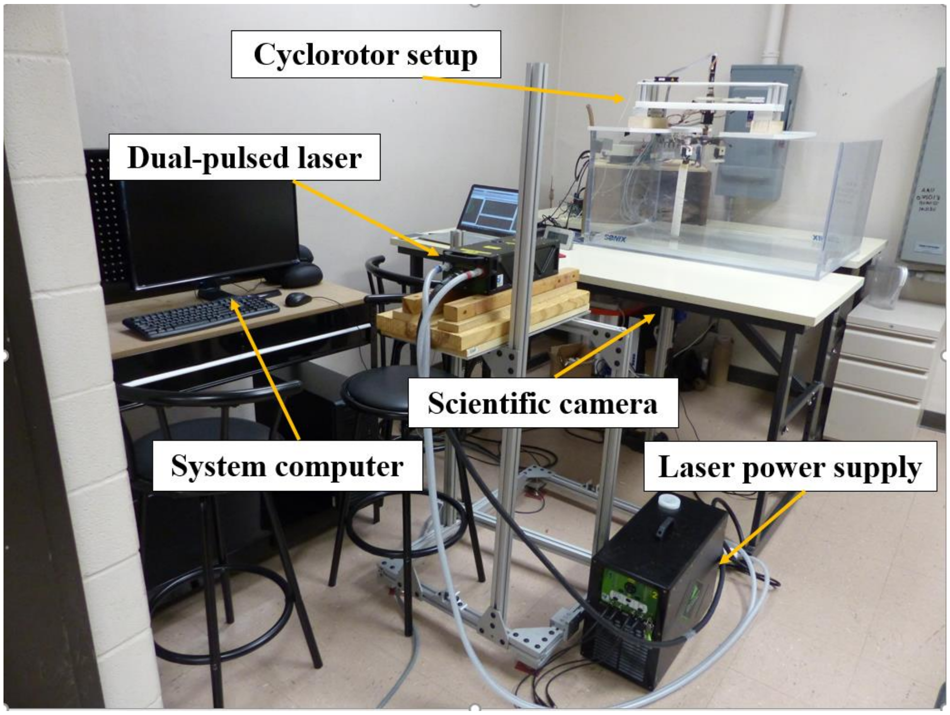

Fig. 1: PIV setup for measuring the flowfield around a cycloidal rotor blade in a water tank at matched Reynolds numbers.

1.3. Programmable Timing Unit

Internal - 16 output channels, 2 input channels, 10 ns time resolution, variable trigger delay for phase-resolved measurements.

1.4. System Computer

(For CamLink and GigE Cameras - PCI-e boards) – including 2 x quad-core XEON processors, 12 GB RAM, DaVis software/camera interface/PTU installation and testing.

1.5. PIV Software Package
Sophisticated multi-pass cross-correlation processing with deformed window correlation and sub-pixel window offset, adaptive PIV.

1.6. Dual Cavity Pulsed Laser and Sheet Optics
Quantel Evergreen PIV 70, 2 x 70 mJ/pulse at 532 nm, 15 Hz pulse rate, single power supply. Laser CLASS 4. Adjustable sheet light optics for 532 nm. Sheet waist focal length infinitely adjustable between 300-2000 mm, two sets of cylindrical lenses: -10 and -20 mm focal lengths

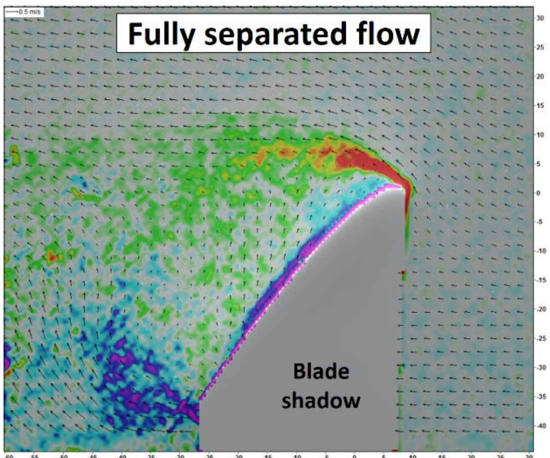

Fig. 2: 45° static pitch: Flowfield showing fully separated flow on a cyclorotor blade with static pitch (measured using the PIV system, **Fig. 1**).

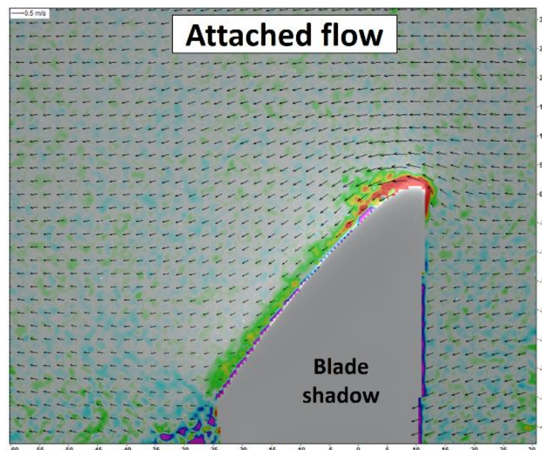

Fig. 3: 45° dynamic pitch: Flowfield showing attached flow on a cyclorotor blade with dynamic pitch (measured using the PIV system, **Fig. 1**).

2. Data Acquisition System

2.1 National Instruments USB-6351
X Series Multifunction DAQ (16 AI, 24 DIO, 2 AO), 1.25 MS/s single-channel sampling rate
2.2 SC-2345
Shielded Carrier with SCC-PWR02 Power Option
2.4 SCC-SG24
2-channel, Full Bridge, 10V Excitation Strain Gauge Module for load cells and strain gauges.
2.5 SCC-FT01
Feedthrough / Breadboard Module which passes signals directly to signal carrier device. Analog input used for sensing shaft encoder position voltage, hall effects sensor voltage, and voltage drop across current sensing resistors.

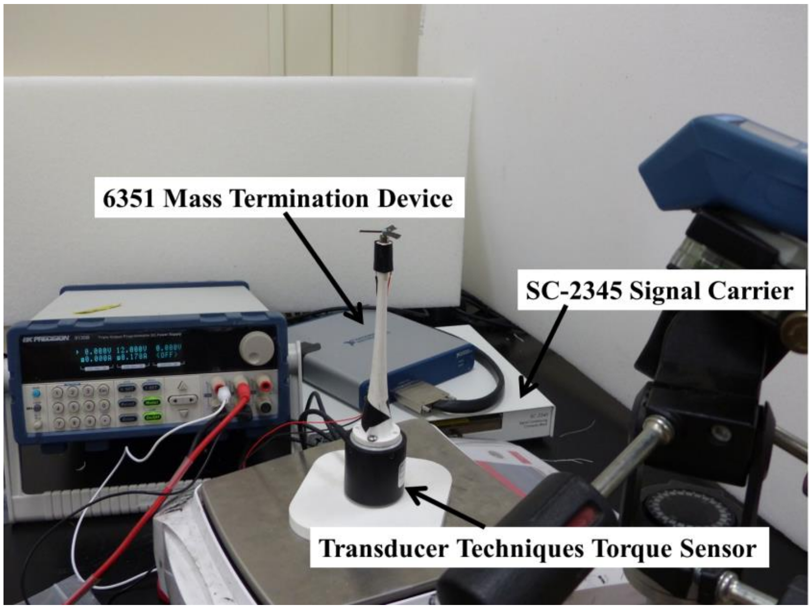

Fig. 4: Experimental setup up for measuring performance of a micro-rotor. Force and torque data collection through signal carrier and mass termination device.

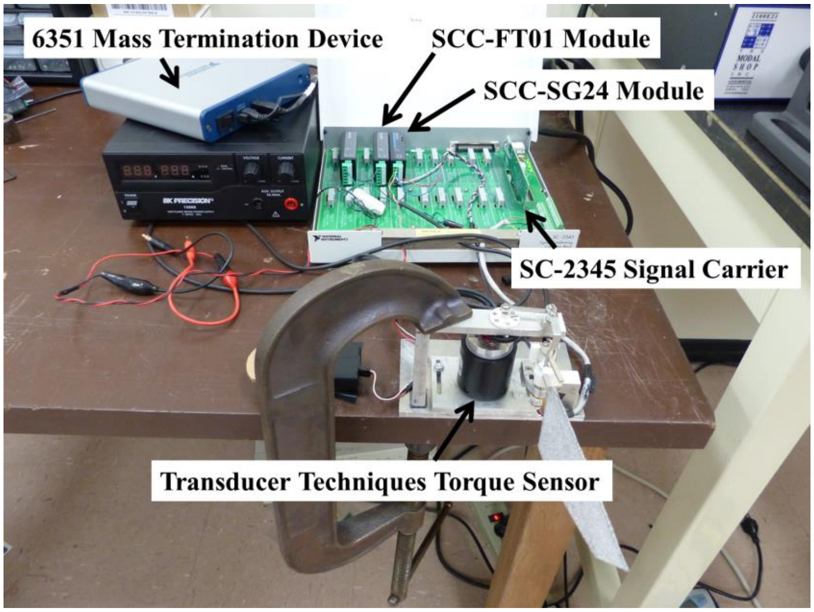

Fig. 5: Experimental setup up for measuring performance of flapping wing. Force, torque, shaft encoder and current data collection through signal carrier and mass termination device.

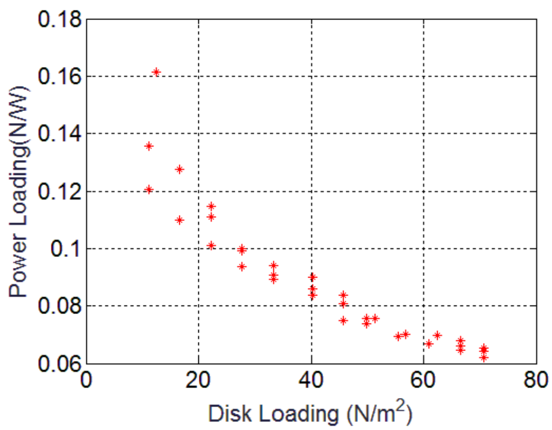

Fig. 6: Variation of power loading with disk loading for a 1-inch diameter micro rotor (measured using setup in **Fig. 4**).

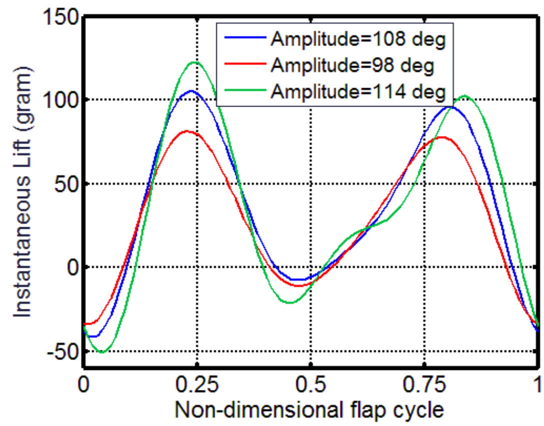

Fig. 7: Instantaneous lift of the flapping wing at 3 different stroke amplitudes (measured using the setup in **Fig. 5**).

3. Micro Pressure Sensors

3.1. Endevco® model 40931 micro pressure sensor

Highly compact (measures 1.65 mm long by 1.2 mm wide by 0.4 mm thick) with 0 to 15 psia range to measure the surface pressure distribution on cyclorotor blade.

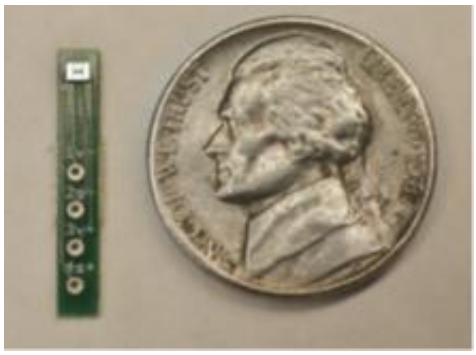

Fig. 8: Model 40931 Silicon MEMS pressure sensor on custom-printed circuit board.

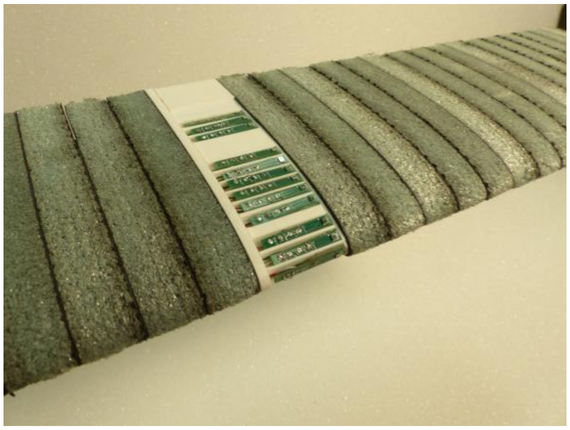

Fig. 9: Micro pressure sensors mounted on sensor panel on cyclorotor blade.

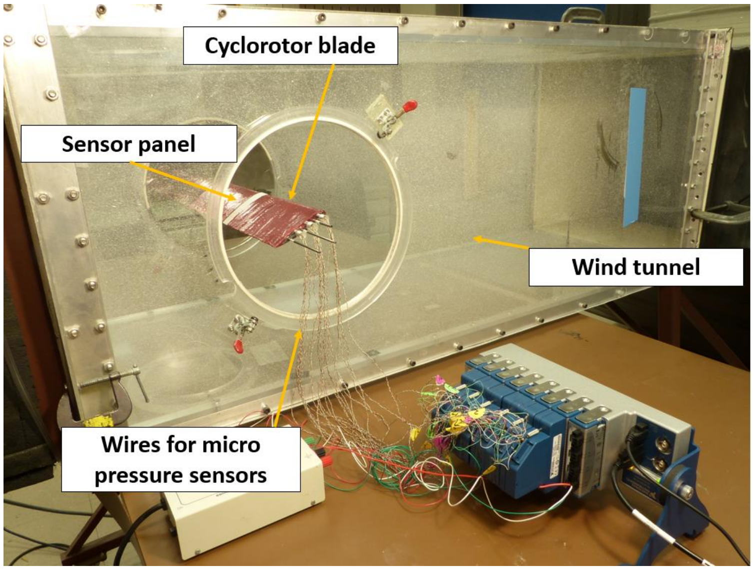

Fig. 10: Wind tunnel setup with pressure sensors mounted on blade.

4. Single-Axis Force/Torque Sensors

4.1 Ultra-Precision mini Load Cell

Transducer Techniques 150 gram axial load force sensor to measure small forces on multicomponent force balances.

4.2 Reaction Torque Sensor

4.2.1 Description: Transducer Techniques (RTS 5, 10, 50 in-oz) torque sensor to measure small forces on multicomponent force balances

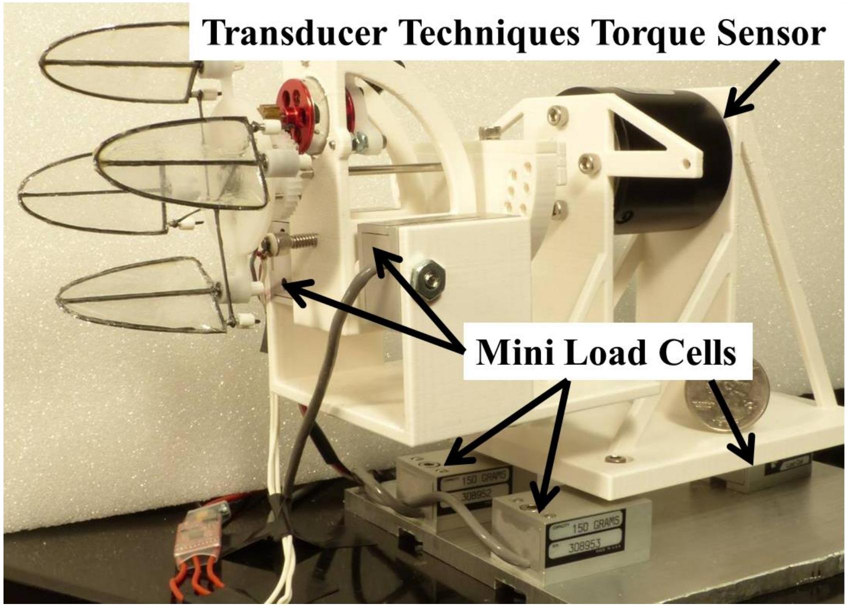

Fig. 11: Experimental setup up for measuring the performance of meso-scale cyclorotors. Mini load cells measure vertical and horizontal forces; torque sensor measures torque.

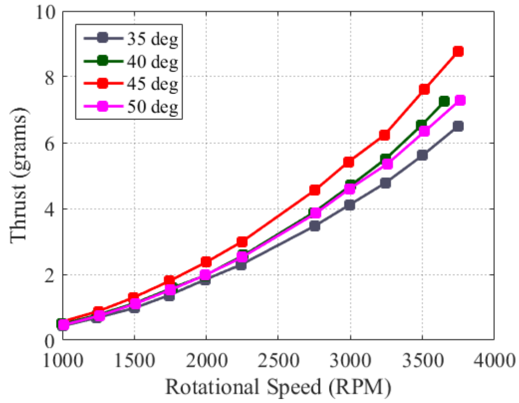

Fig. 12: Thrust produced by cyclorotor vs. rpm at different blade pitch amplitudes (obtained using the setup in **Fig. 11**).

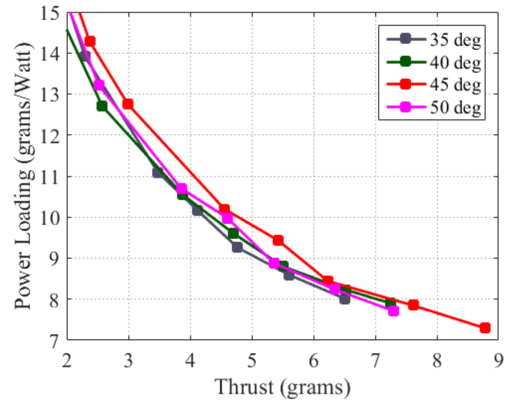

Fig. 13: Power loading vs. thrust for the cyclorotor at different blade pitch amplitudes (obtained using the setup in **Fig. 11**).

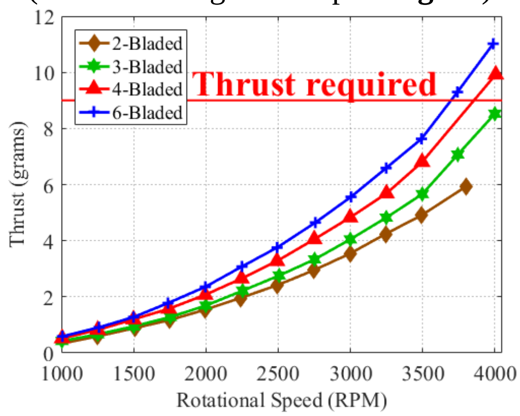

Fig. 14: Thrust produced by cyclorotor vs. rpm in for different number of blades (obtained using the setup in **Fig. 11**).

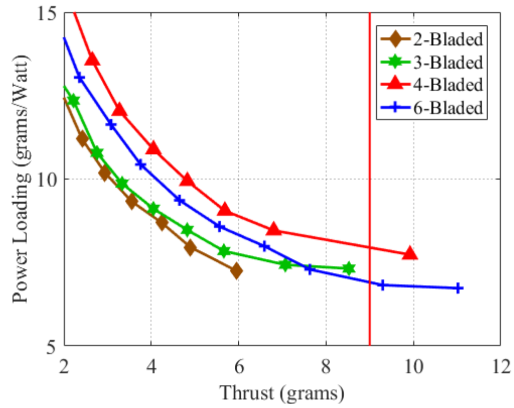

Fig. 15: Power loading vs. thrust for cyclorotors with different number of blades (obtained using the setup in **Fig. 11**).

5. Miniature 6-Axis Force Balance

5.1. Miniature 6-axis Transducer

Multi-axis force and torque sensor system that simultaneously measures forces (Fx, Fy, and Fz) and torques (Tx, Ty, and Tz). Other necessary components include interface and power supply box, as well as cable to transmit transducer data to DAQ. Allows for instantaneous aerodynamic blade loads to be measured at blade root. Provides us with a better understanding of the unsteady aerodynamic phenomena on cycloidal rotor blades.

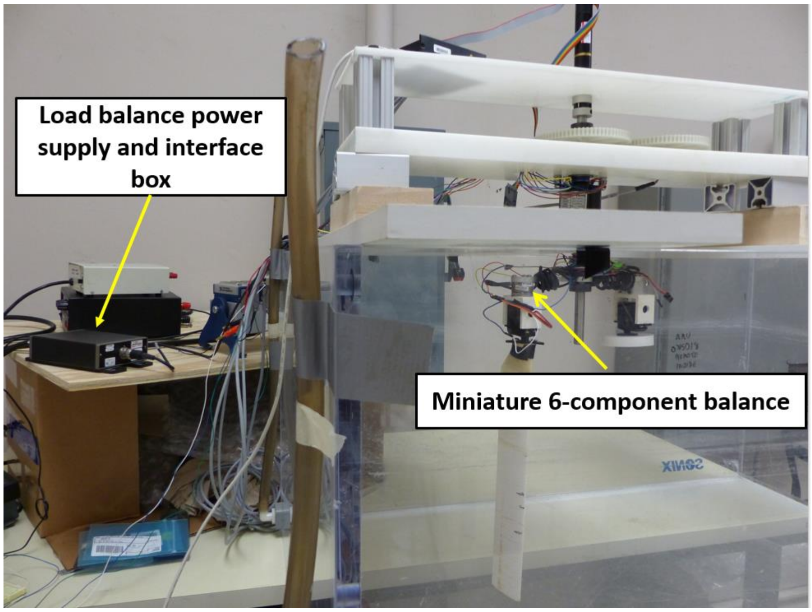

Fig. 16: Miniature 6-axis force balance setup at the cyclorotor blade root.

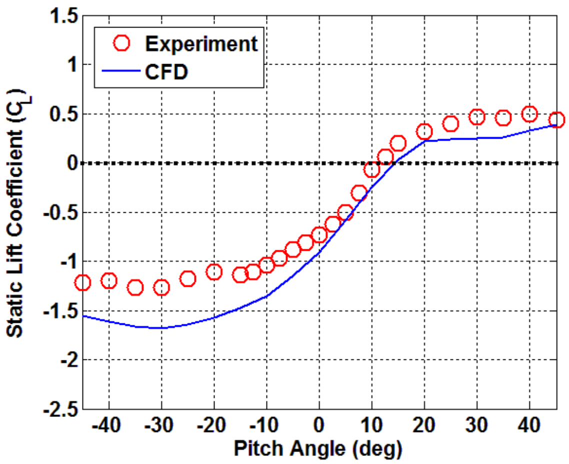

Fig. 17: Static pitch: Lift coefficient of a cyclorotor blade vs. static pitch angle (measured using six-component balance, **Fig. 16**).

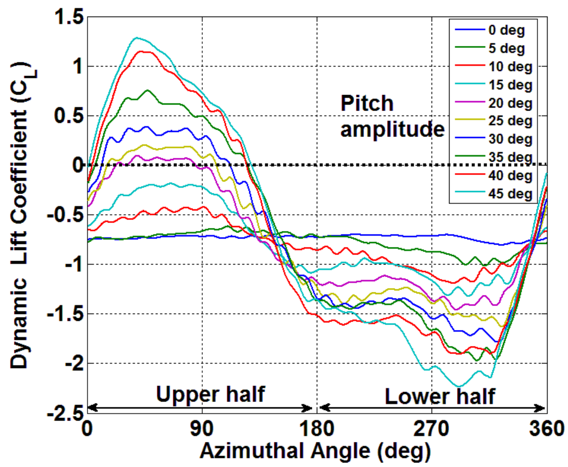

Fig. 18: Dynamic pitch: Lift coefficient of a cyclorotor blade vs. blade azimuthal location for dynamic pitching (measured using six-component balance, **Fig. 16**).